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(54) **INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR**

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See application file for complete search history.

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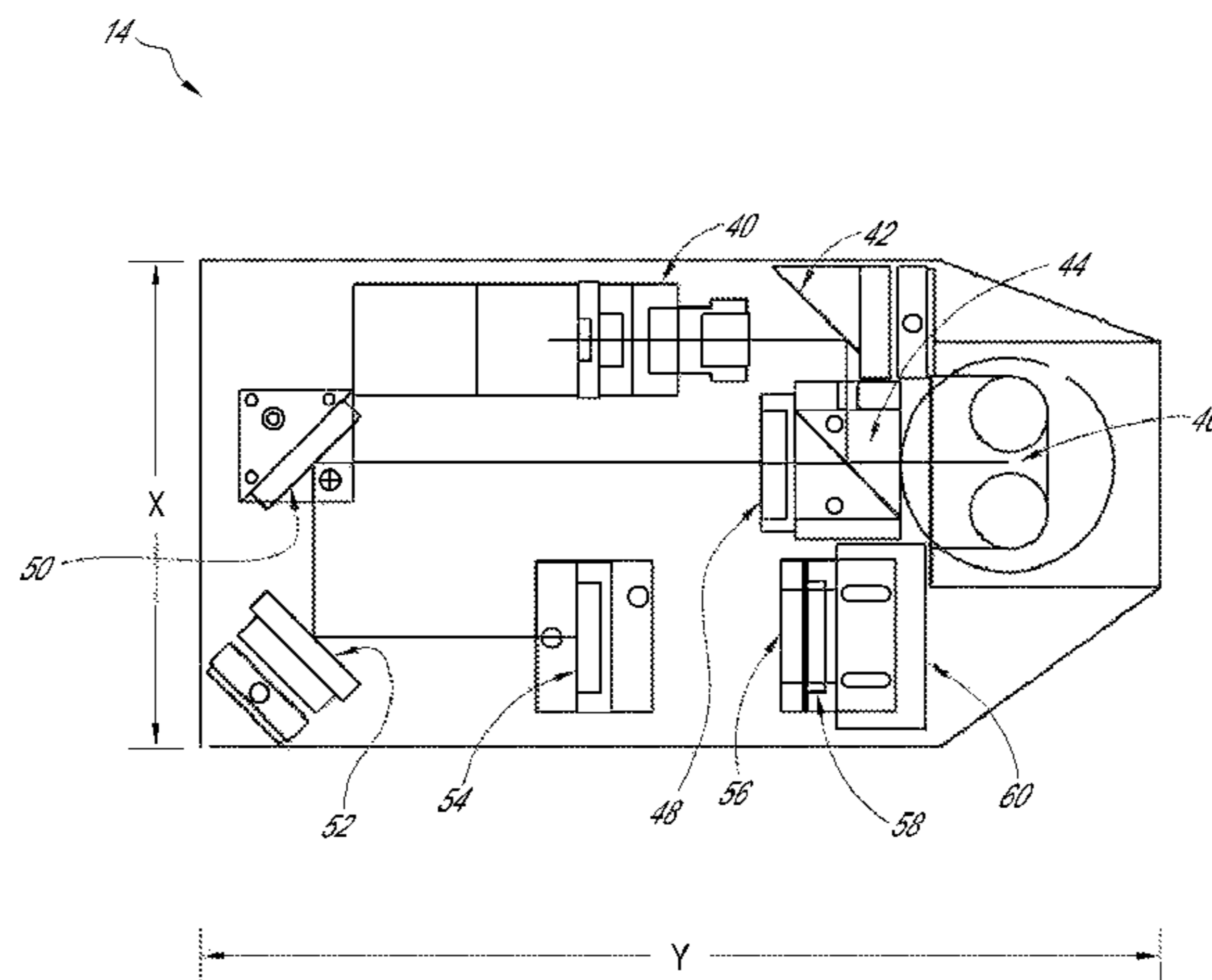
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(57) **ABSTRACT**

A wavefront sensor is integrated with a surgical microscope for allowing a doctor to make repeated wavefront measurements of a patient's eye while the patient remains on an operating table in the surgical position. The device includes a wavefront sensor optically aligned with a surgical microscope such that their fields of view at least partially overlap. The inclusion of lightweight, compact diffractive optical components in the wavefront sensor allows the integrated device to be supported on a balancing mechanism above a patient's head during a surgical procedure. As a result, the need to reposition the device and/or the patient between measuring optical properties of the eye and performing surgical procedures on the eye is eliminated. Many surgical procedures may be improved or enhanced using the integrated device, including but not limited to cataract surgery, Conductive Keratoplasty, Lasik surgery, and corneal corrective surgery.

13 Claims, 5 Drawing Sheets



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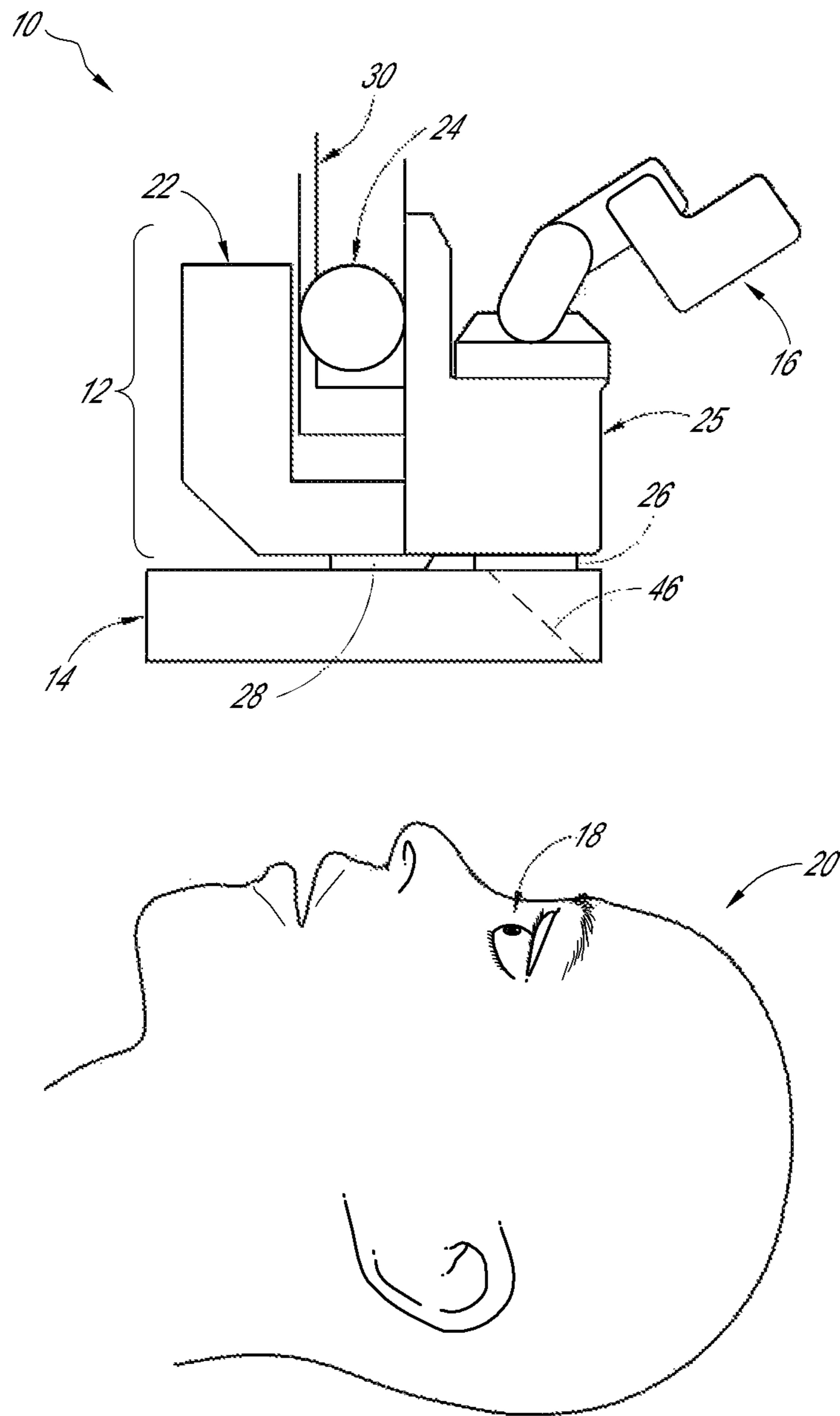


FIG. 1

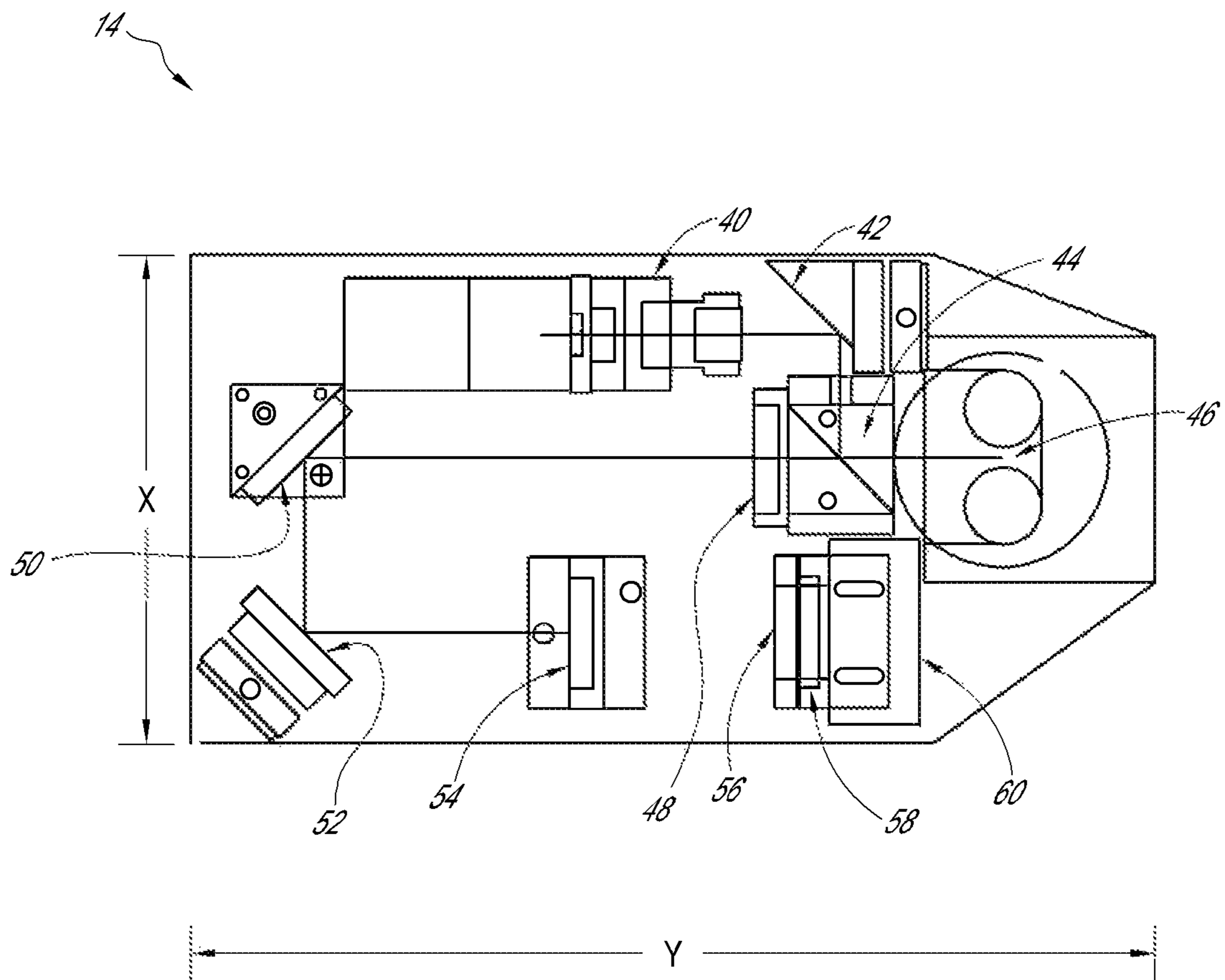


FIG. 2

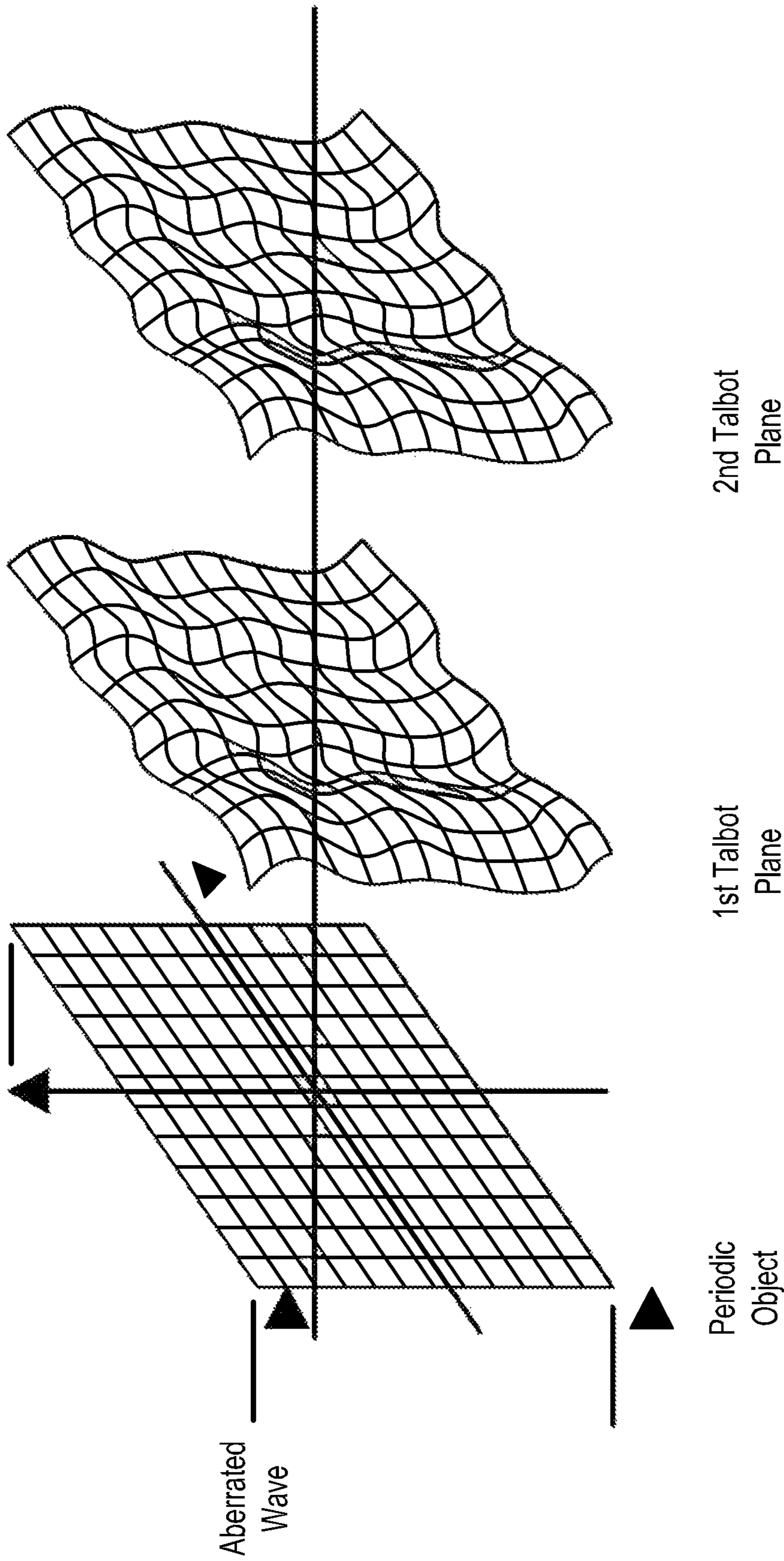


FIG. 3

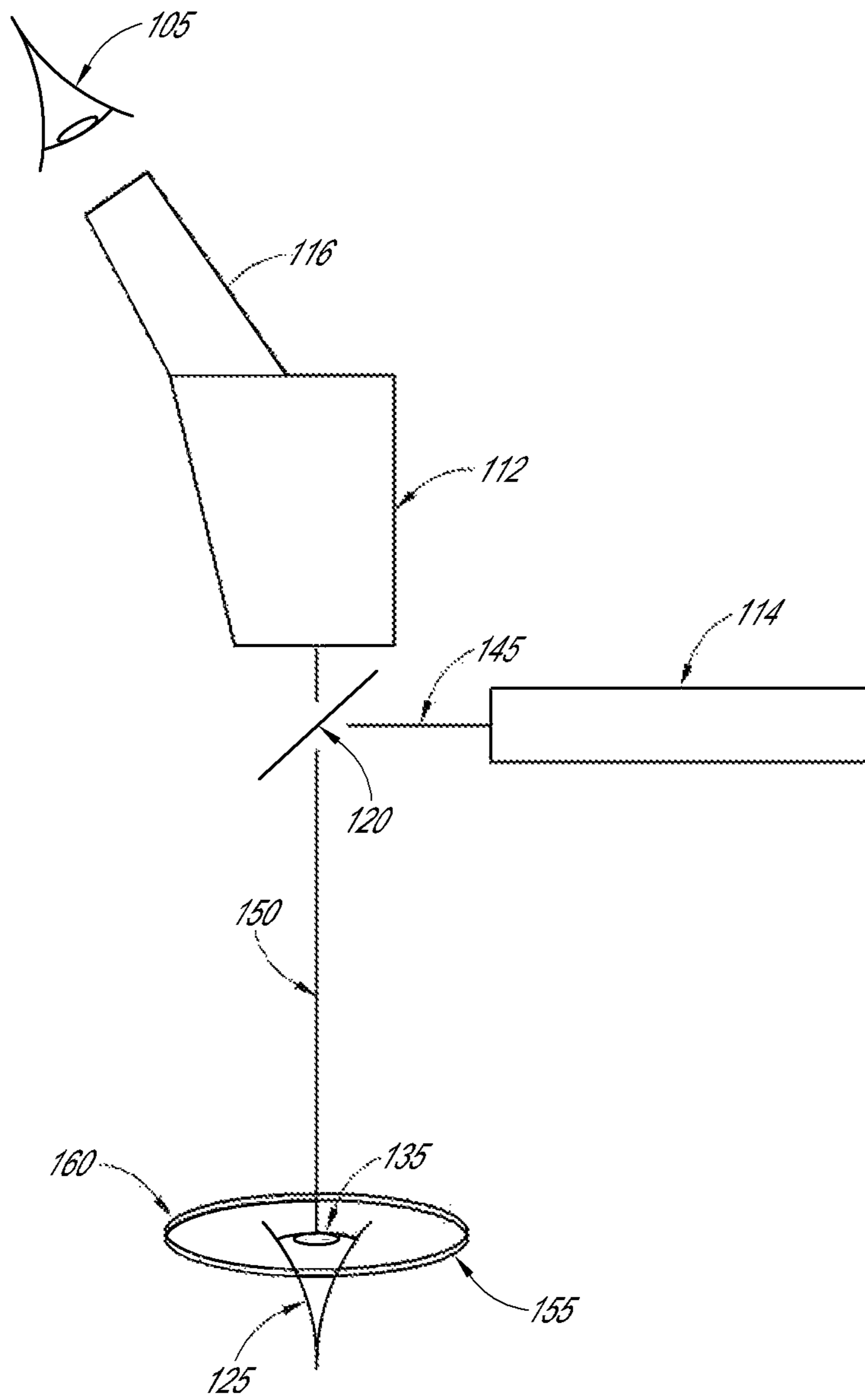


FIG. 4

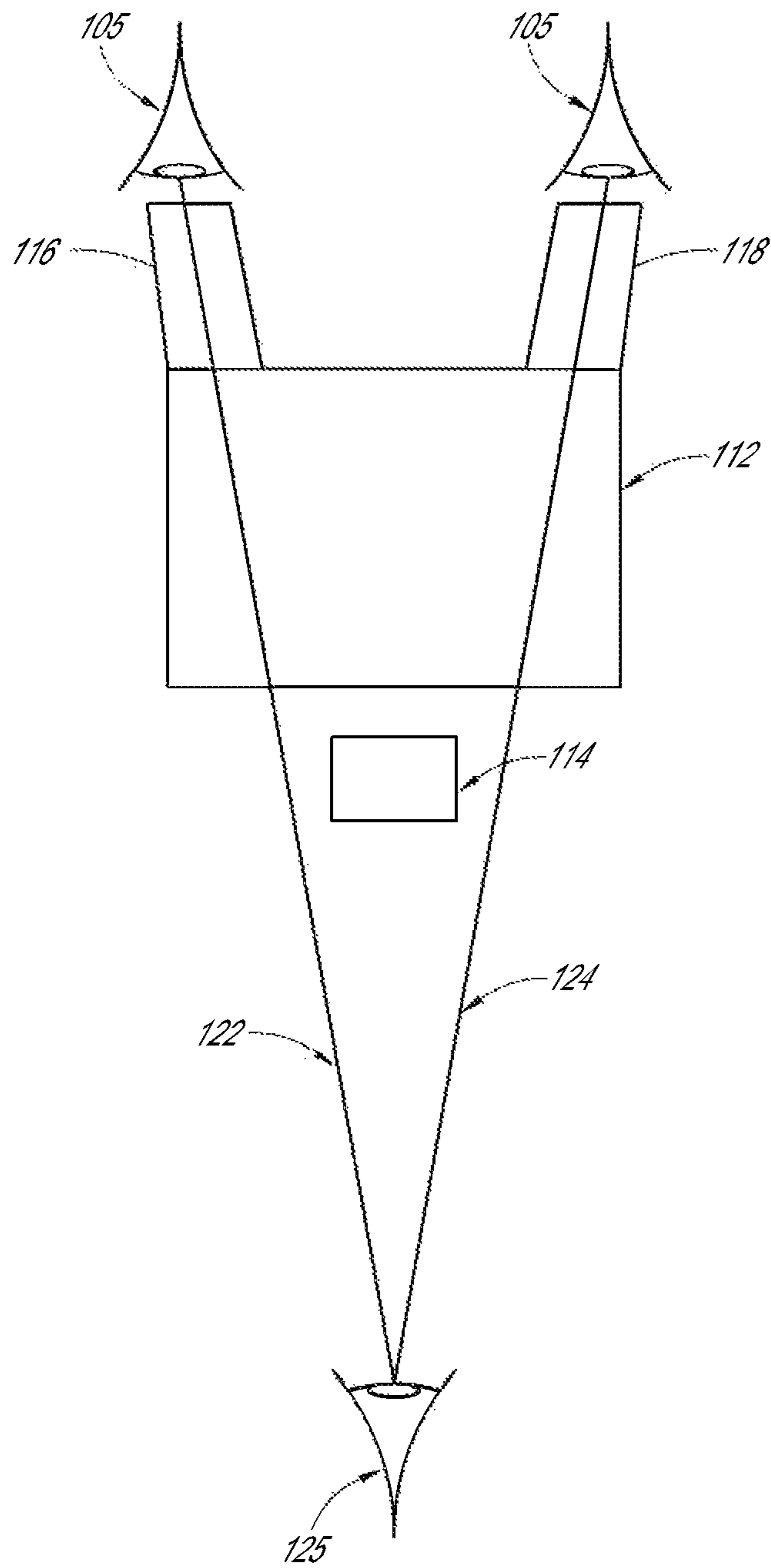


FIG. 5

INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR

INCORPORATION BY REFERENCE TO ANY PRIORITY APPLICATIONS

Any and all applications for which a foreign or domestic priority claim is identified in the Application Data Sheet as filed with the present application, are hereby incorporated by reference under 37 CFR 1.57. Specifically, this application is a continuation of U.S. patent application Ser. No. 13/797,365, entitled "INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR," and filed Mar. 12, 2013, which is a continuation of U.S. patent application Ser. No. 13/619,168, entitled "INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR," and filed Sep. 14, 2012, which is a continuation of U.S. patent application Ser. No. 13/021,594, entitled "INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR," and filed Feb. 4, 2011, which is a continuation of U.S. patent application Ser. No. 11/110,653, entitled "INTEGRATED SURGICAL MICROSCOPE AND WAVEFRONT SENSOR," and filed Apr. 20, 2005, which claims the benefit of U.S. Provisional Application No. 60/563,727, filed Apr. 20, 2004, each of which is incorporated by reference in its entirety.

BACKGROUND

Refractive surgery and other corrective procedures are commonly performed on the human eye. During a refractive surgical procedure, the refractive quality of the eye is altered. The goal of refractive surgery typically is to correct a defective refractive condition of the eye, while not diminishing the overall refractive quality of the eye. In some cases, the goal is to actually improve the overall refractive quality of the eye.

Refractive measurements are typically taken with phoropters, pachymeters, corneal topographers, autorefractors, keratometers, and/or wavefront sensors. Of these devices, wavefront sensors generally provide the greatest detail about the refractive condition of, and additional information relating to, the eye. Wavefront sensors are generally standalone devices that operate in relatively large areas dedicated to the use of the wavefront sensors. With most existing wavefront sensors, the patient's eye is measured while the patient is in a sitting position.

Many methods of performing refractive eye surgery require pre-operatively measuring the refractive quality of a patient's eye using a wavefront sensor or other measuring device. This refractive quality information is used to plan a detailed refractive surgical procedure. The patient is then typically moved from the wavefront sensor location to a surgical location, where the patient lies supine in the "surgical position." During the refractive surgical procedure, the surgeon may view the patient's eye through a surgical microscope or other viewing device, which typically is suspended above the patient's head via a balancing mechanism or other similar device. Once the refractive surgical procedure is completed, the patient is typically moved back to the wavefront sensor location, and the eye is measured to determine the outcome of the surgery.

Although measuring the refractive quality of the eye after the refractive surgery has been performed provides a quantification of the outcome of the surgery, it does not allow modifications to the surgery to be performed while the patient remains in the surgical position. If the outcome is not ideal, the patient may be relocated to the surgical area for a re-treatment, but in many cases a re-treatment may not be as

effective as if the procedure had been performed to produce an ideal result the first time before the patient was moved from the surgical position. Additionally, moving a patient out of the sterile surgical field for diagnostic purposes, and then back into the surgical field, can be problematic.

If the refractive quality of the eye could be measured repeatedly as the surgery is progressing, without moving the patient, the surgeon would have the opportunity to judge whether the procedure was producing desired results at the expected rate, and would be able to make adjustments or course corrections to the procedure midstream to improve the likelihood of achieving the desired outcome. Unfortunately, existing wavefront sensors and other measuring devices are generally relatively large and heavy, making them impracticable or impossible to suspend above a patient's head during surgery. As a result, a patient must be physically moved between wavefront measurement procedures and surgical correction procedures that are typically performed under a surgical microscope.

While attempts have been made to integrate a microscope into a comprehensive treatment and measurement device, such devices are typically very large, heavy, and cumbersome, such that they cannot be practically suspended above a patient lying in the surgical position. These devices also typically include shared lenses and other optical components. The sharing of optical components in this manner generally obscures the overall quality of the measurements that are produced, since each device component typically has its own set of optical requirements that cannot each be optimally satisfied using shared lenses and so forth. Thus, a need exists for an improved device for measuring and evaluating refractive and other optical properties and characteristics of an eye.

SUMMARY

A wavefront sensor is integrated with a surgical microscope for allowing a doctor to make repeated measurements of a patient's eye while the patient remains in a surgical position. The device includes a wavefront sensor optically aligned with a surgical microscope such that their fields of view at least partially overlap. The optional inclusion of lightweight, compact diffractive optical components in the wavefront sensor allows the integrated device to be supported on a balancing mechanism above a patient's head during a surgical procedure. As a result, the need to reposition the device and/or the patient between measuring optical properties of the eye and performing surgical procedures on the eye is eliminated.

Other features and advantages of the invention, including methods of using the device described above, will appear hereinafter. The features of the invention described above can be used separately or together, or in various combinations of one or more of them. The invention resides as well in sub-combinations of the features described.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, wherein the same reference number indicates the same element throughout the several views:

FIG. 1 is a side view of an integrated wavefront sensor and surgical microscope positioned above a patient's head.

FIG. 2 is a top view of the internal components of a wavefront sensor (with the cover removed) according to one embodiment.

FIG. 3 is a perspective view of an aberrated wave traveling through a grating, as well as wave images produced at the first and second Talbot planes of the grating.

FIG. 4 is a side-view schematic diagram illustrating the operation of an integrated wavefront sensor and surgical microscope according to one embodiment.

FIG. 5 is a front-view schematic diagram of the operation of the integrated wavefront sensor and surgical microscope illustrated in FIG. 4.

DETAILED DESCRIPTION

Various embodiments of the invention will now be described. The following description provides specific details for a thorough understanding and enabling description of these embodiments. One skilled in the art will understand, however, that the invention may be practiced without many of these details. Additionally, some well-known structures or functions may not be shown or described in detail so as to avoid unnecessarily obscuring the relevant description of the various embodiments.

The terminology used in the description presented below is intended to be interpreted in its broadest reasonable manner, even though it is being used in conjunction with a detailed description of certain specific embodiments of the invention. Certain terms may even be emphasized below; however, any terminology intended to be interpreted in any restricted manner will be overtly and specifically defined as such in this detailed description section.

Referring to FIG. 1, a surgical device 10 includes a surgical microscope 12, or other suitable viewing device, attached to a wavefront sensor 14, or other measuring device. The surgical microscope 12 includes an eyepiece 16, or other viewing mechanism, which includes one or more optical channels each having one or more optical lenses therein. The eyepiece 16 is preferably binocular, or stereo, in that it includes two optical channels for allowing a doctor to view an eye 18 of a patient 20 using both of the doctor's eyes (as is best seen in FIG. 5). While a monocular eyepiece may alternatively be used, a binocular eyepiece is generally preferred because it provides a higher quality, more complete view to the doctor.

The surgical microscope 12 preferably further includes a light source 22 for providing visible light into the optical pathway of the eyepiece 16, a focusing knob 24 for adjusting the focus of the microscope 12, and an objective lens 26, or other suitable lens, for focusing light beams. In one embodiment, the objective lens 26 is threaded onto the microscope 12 via internal threads on the lens 26 that match external threads on a body 25 of the microscope 12.

The wavefront sensor 14 may be attached to the microscope 12 in any suitable manner, and is preferably removably attached to the microscope 12. For example, the objective lens 26 may be removed from the microscope 12, and the wavefront sensor 14, which preferably includes an attachment portion with interior threads that match the exterior threads of the microscope body 25, may be screwed onto the external threads of the microscope 12. The objective lens 26 may then be screwed back onto the external threads beneath the attachment portion of the wavefront sensor 14. One or more fasteners 28 may optionally be included to further (or alternatively) secure the wavefront sensor 14 to the microscope 12. The wavefront sensor 14 may alternatively be attached to the microscope via screws, bolts, pins, clamps, adhesive, or any other suitable fasteners or attachment means.

Referring to FIG. 2, the interior of one embodiment of a wavefront sensor 14 is illustrated. The wavefront sensor 14 includes a laser source 40, or other light source, for creating a beam of light, preferably infrared light. During operation, the beam of infrared light is preferably directed by a mirror 42 toward a beam splitter 44 or other suitable device. An aper-

ture-sharing element, such as a combiner mirror 46 (shown in dashed lines in FIG. 1), a beam-splitter, or other similar device, reflects the beam of infrared light down into the eye 18 of the patient 20. The combiner mirror 46 preferably reflects infrared light while transmitting visible light so that a doctor can see the patient's eye 18 while looking through the combiner mirror 46. The combiner mirror 46 may alternatively be configured to reflect a portion of the visible light spectrum, and/or to transmit a portion of the infrared light spectrum, as described below.

After the infrared light beam enters the eye 18, it is reflected, as a wavefront, from the retina of the eye 18 toward the combiner mirror 46. The combiner mirror 46 redirects the light beam through the beam splitter 44 toward a first lens 48. The first lens 48 relays the infrared light beam off of mirrors 50 and 52 toward a second lens 54, which directs the light beam onto a diffractive optical component, such as a first reticle or grating 56. The mirrors 42, 50, 52 are optionally included in the wavefront sensor 14 for re-directing the light beam to maintain it within a compact area, which facilitates the minimization of the overall size and length of the wavefront sensor 14. A greater or lesser number of mirrors may be included in the wavefront sensor 14.

The light beam is diffracted by the first grating 56, as described in detail below, and preferably travels through another diffractive optical component, such as a second grating 58, which further diffracts the light beam and creates a final image of the wavefront reflected from the eye 18. A camera 60, and/or another light detector or sensor, such as a CCD camera or other suitable device, then captures, records, and/or detects the final image of the eye 18 and converts it into a computer-readable format. A computer may then measure and analyze the data to quantify characteristics of the wavefront, and thus, the refractive properties of the eye being examined.

The wavefront sensor 14 may of course include a greater or lesser number of components to meet the requirements of a given system. For example, a greater or lesser number of diffractive gratings or optical lenses may be included in the wavefront sensor 14. Moreover, additional optical components, such as a camera lens, may optionally be included between the second refractive grating 58 and the camera 60. Thus, the specific configuration of the wavefront sensor 14 illustrated in FIG. 2 is only one example a suitable wavefront sensor configuration.

Because the wavefront sensor 14 requires relatively few components, and uses relatively small, lightweight diffractive optical elements in its wavefront analysis section, the wavefront sensor 14 may be very compact and lightweight, and can produce higher resolution and more accurate alignment registration than a wavefront sensor using larger conventional refractive optics, such as a typical Hartmann-Shack wavefront sensor, as described below. The wavefront sensor 14 preferably has a length Y that is less than 10 inches, more preferably less than nine inches, more preferably approximately 8.5 inches, and a width X that is preferably less than 5 inches, more preferably approximately 4.5 inches. The wavefront sensor 14 preferably weighs less than five pounds, more preferably less than 3 pounds or less than 2 pounds. The wavefront sensor 14 may of course be any other suitable size and/or weight.

Due to its relatively low weight and small size, the wavefront sensor 14 may be directly or indirectly attached to the surgical microscope 12 to form an integrated surgical device 10. In this sense, the term "integrated" generally refers to the wavefront sensor 14 and the surgical microscope 12 being incorporated into a unit. The integrated surgical device 10

may be attached to a balancing mechanism, hanging mechanism, or other suitable device or stand for suspending the integrated device **10** over a patient's head during surgery. The balancing mechanism or other supporting device may be spring-loaded, counter-balanced, or otherwise balanced for supporting the integrated device **10**. Balancing mechanisms of this nature are commonly used to support and suspend surgical microscopes.

To secure the integrated surgical device **10** to a balancing mechanism, an attachment portion **30** of the surgical microscope **12** (or of the wavefront sensor **14**) may be attached to the balancing mechanism via screws, pins, bolts, or other suitable fasteners, or the integrated device **10** may be attached to the balancing mechanism in any other suitable manner. In one embodiment, the wavefront sensor **14** may be added to an existing surgical microscope **12** that is already supported on a balancing mechanism. The field of view and the focal length of the microscope **12** and/or the wavefront sensor **14** may then be adjusted, if necessary, to optically align the devices relative to one another, as further described below.

Generally speaking, refractive optical components are used to redirect a light beam as it passes through a material having a higher density than air, such as a glass refractive lens. Diffractive optical components, conversely, are used to bend a light beam as it encounters the sharp edges of an element, such as the gratings **56**, **58**, and only portions of the light beam occurring near the edges of the grating or other object are redirected. Diffractive optical components, such as gratings, are typically significantly smaller and weigh less than refractive optical components, such as refractive lenses.

The one or more diffractive gratings used in the wavefront sensor **14** may be made of any suitable material. A preferred diffractive grating is made from a clear material, such as glass, and has equally spaced perpendicular lines etched or otherwise present on its surface. The grating may include, for example, a repeating sequence of solid lines each having a width of approximately 12.5 microns, with each pair of lines separated by approximately 12.5 microns of clear glass (the lines and glass spaces on the grating may of course have any other suitable dimensions). The same sequence is repeated with lines running perpendicularly to the first set of lines, such that a pattern similar to that of a standard grid (i.e., a network of uniformly spaced horizontal and perpendicular lines) is formed.

As illustrated in FIG. 3, when a wavefront of light reflected from an eye encounters a grating (referred to as the "Periodic Object" in FIG. 3) diffractive effects begin to occur. Some of the light hits the solid portions of the lines on the grating and is prevented from passing through the grating. Some of the light passes cleanly through the clear spaces in the grating and is not affected by the grating lines. The remaining light, however, encounters the edges of the solid lines as it passes through the grating. This light is disturbed by the lines and is deflected away from the central core of the light that passes cleanly through the clear spaces in the grating.

This redirected light encounters light that has been redirected by one or more adjacent grating lines. When portions of light directed from equally spaced lines meet one another, a phenomenon known as the "Talbot Effect" occurs, and a series of dark and light zones form in a space within a predictable distance downstream from the grating, at locations referred to as Talbot planes. This phenomenon is described in detail in U.S. patent application Ser. No. 10/885,504, filed Jul. 6, 2004, as well as in "Fourier Transform Method For Automatic Processing of Moire Deflectograms," Quiroga et al., Opt. Eng. 38(6) pp. 974-982 (June 1999), and in "Refractive Power Mapping of Progressive Power Lenses Using Talbot

Interferometry and Digital Image Processing," Nakano et al., Opt. Laser Technology. 22(3), pp. 195-198 (1990), all of which are incorporated herein by reference.

If the wavefront of light that passed through the grating is a flat, plane wave, the dark and light zones form a perfect replica of the grating, i.e., a virtual image of the grating. If, however, the wavefront is aberrated or includes any deviations from a flat, plane wave, the shape and size of the virtual image of the grating is distorted, as shown in FIG. 3. By observing the distortions in the shape and size of the virtual image created by the grating, the characteristics of the wavefront can be determined. The virtual image may be observed by a camera or other light detector, and the images may be measured, typically by a computer, to accurately quantify the characteristics of the wavefront, and hence, the refractive properties of the eye being examined.

In one embodiment, two or more gratings are aligned in series in the wavefront sensor. By causing the virtual image to pass through the line patterns in one or more additional gratings, the virtual image of the grating is modified to show less resolution, which can compensate for a camera having insufficient resolution. Additionally, by adding one or more gratings, and rotating the downstream gratings with respect to one another, the changes in the virtual image of the initial grating are visually converted into rotational movement, rather than just shrinkage or expansion, and the characteristics of the wavefront may be determined without change in size of the virtual image.

The virtual image created by the gratings contains, simultaneously, two sets of information. The first set of information is the virtual image of the grating from which the refractive properties of the eye are characterized, as described above. The second set of information is an almost complete image of the pupil of the eye, which is comprised of the light that passed untouched through the clear spaces of the grating, as well as light that reflected from the surface of the pupil, the sclera, the limbus, and/or other features of the eye if additional illumination is directed to illuminate these features. This image essentially appears to be that of an eye being observed with a grid (i.e., a network of uniformly spaced horizontal and perpendicular lines) between the eye and the observer.

Referring to FIGS. 4 and 5, a schematic representation of a process for measuring characteristics of an eye is shown. A surgeon (or other doctor) **105** looks through a surgical microscope **112** at the eye **125** of a patient. The surgical microscope **112** preferably includes binocular, or stereo, optics such that it includes two optical viewing channels **116**, **118** (as shown in FIG. 5). A monocular microscope may alternatively be used, however. Visible light reflecting from the patient's eye **125** travels along a light pathway **150**, passes through a combiner mirror **120** or similar device, and into the microscope **112**, so that the surgeon may view the patient's eye **125** along visual pathways **122**, **124**.

A wavefront sensor **114** generates an infrared light beam and projects it outwardly along a pathway **145** toward the combiner mirror **120**. While the combiner mirror **120** is shown located outside of the wavefront sensor **114** in the schematic representation of FIGS. 4 and 5, it is understood that the combiner mirror **120** may be located inside the wavefront sensor **114**, as is shown in FIGS. 1 and 2, or in any other suitable location where the optical pathways of the surgical microscope **112** and the wavefront sensor **114** meet.

The combiner mirror **120** is preferably transparent to visible light but reflective to infrared light so that it reflects the infrared light beam toward the patient's eye **125**. The wavefront sensor **114** and the microscope **112** preferably share a

common aperture through the combiner mirror **120**. Alternatively, a beam splitter that transmits and reflects both a portion of the visible light and a portion of the infrared light may be used in place of the combiner mirror **120**. Using such a beam splitter would allow the wavefront sensor **114** to operate at a wavelength other than that of the infrared light, such as at a wavelength in the visible spectrum.

In another embodiment, the combiner mirror **120** may be configured to reflect a portion of the visible light spectrum, allowing the wavefront sensor **114** to operate in a wavelength range within the visible spectrum, yet prevent that particular wavelength from entering the Microscope **112**. In yet another alternative embodiment, the combiner mirror **120** may be a narrow pass/reflect combiner, which reflects only a defined wavelength of light having a lower and upper range, thereby allowing the wavefront sensor **114** to operate within the visible light spectrum. The defined visible light spectrum would then be selectively blocked from returning to the microscope **112**, while all light above or below the lower and upper ranges would be freely transmitted.

The combiner mirror **120** reflects the light beam along pathway **150** toward the patient's eye **125**. The infrared light enters the patient's eye **125** and is reflected as a wavefront back along light pathway **150** toward the combiner mirror **120**, which reflects the wavefront along light pathway **145** into the wavefront sensor **114**. The wavefront sensor **114** then measures the wavefront using the process described above, or using a similar process. The wavefront sensor **114** may have the same configuration and components as the wavefront sensor **14** illustrated in FIG. 2, or it may have an alternative configuration and may include alternative components.

The wavefront sensor **114** and the microscope **112** are each preferably focused at a point occurring at plane **135**, such that a field of view **155** of the wavefront sensor **114** at least partially overlaps a field of **160** of the microscope **112**. During measuring, viewing, and/or performing surgery, the patient's eye **125** is preferably located within the overlapping portion of the fields of view **155**, **160**. In a preferred embodiment, the wavefront sensor **114** and the microscope **112** are focused at substantially the same point, such that the center of each field of view **155**, **160** is located at approximately the same point, in the same plane **135**, preferably at or near the center of the patient's eye **125**.

As a result, the surgeon **105** may look through the microscope **112** directly into the visual axis of the patient's eye **125** while the wavefront sensor **114** takes measurements of the eye **125**. Furthermore, because the fields of view **155**, **160** overlap at the patient's eye **125**, the patient does not have to change the gaze angle of the patient's eye **125** at any time during the viewing and measurement processes. This can be very advantageous, especially when the surgical procedure being performed prevents the patient from seeing clearly, or at all, such that it is nearly impossible for the patient to accurately adjust the gaze angle of the patient's eye **125** according to a surgeon's instructions.

The integrated wavefront sensor and surgical microscope described herein provides several advantages. First, it allows a surgeon or other doctor to directly view a patient's eye while the wavefront sensor performs measurements of the refractive characteristics or other optical properties of the patient's eye. As a result, a surgeon can view the results of a given step of a surgical procedure without having to move the patient, the patient's eye, or the device. Indeed, the gaze angle of the patient's eye does not need to change at all during the viewing and measuring steps, and the surgeon's view may be directly aligned with, as opposed to offset from, the visual axis of the patient's eye.

Additionally, due to the relatively small number of components used in the wavefront sensor, and the relatively small size and low weight of those components, particularly of the one or more lightweight diffractive gratings or other diffractive optical components, the integrated device may be very compact. Accordingly, the lightweight integrated device can be suspended on a balancing device, or other supporting mechanism, above the head of a patient lying in the supine surgical position, while the surgeon views the patient's eye through the surgical microscope of the integrated device.

To maintain its compact size and design flexibility, the integrated surgical device **10** is preferably not integrated with or otherwise attached to a refractive laser device or other refractive surgical tool. Thus, the integrated surgical device **10** is preferably used primarily for viewing and measuring purposes, while one or more surgical tools used to perform corrective eye procedures are physically separate from the integrated device. Lightweight or otherwise compact surgical tools, however, may optionally be incorporated into the surgical device **10**. The wavefront sensor **14** and the surgical microscope **12** also preferably do not share an optical pathway to the patient's eye **18** with any other surgical devices.

Because the wavefront sensor and the surgical microscope are preferably (although, not necessarily) separate components that are removably attached to one another, they may each include their own optical components, including any lenses. Thus, the wavefront sensor and the surgical microscope do not need to share a lens, thus providing several advantages and general design flexibility over integrated surgical systems that require one or more lenses to be shared between two or more optical components.

Some surgical systems, for example, use a common optical lens to focus light beams from both a wavefront sensor and a refractive laser device. By sharing a lens in this manner, the flexibility to select or design the lens for only a single specific function is lost, as is the ability to design the best possible lens for the overall system application. By using a common lens, compromises must be made to meet the requirements of each component that shares the lens.

Antireflective coatings, for example, are commonly applied to lenses so that they can function optimally within a certain wavelength. If the laser being used is of a different wavelength than the wavefront sensor illumination beam, however, a common antireflective coating cannot be selected that will work optimally for each of the wavelengths. The same holds true for the wavelength of the wavefront sensor illumination beam in comparison to that of the visible light used to provide visibility through a microscope. Because the surgical device **10** described herein does not require that a lens be shared between the wavefront sensor and the surgical microscope, different antireflective coatings may be applied to the lenses of each of these components, thus allowing for optimal coatings to be selected for each component.

Another disadvantage of sharing a common lens between two or more optical components is the inability to select an optimal focal length, or power, of the lens for each component involved. In many cases, a long focal length lens is desirable in a wavefront sensor to provide sufficient working space for a doctor between the wavefront sensor and the patient. With many refractive lasers, conversely, a shorter focal length lens is desirable to more tightly focus the laser energy into a shorter plane. A system that shares a common lens for these components must compromise or settle on a common focal length, which will not be optimal for one or both of the components.

Additionally, if a wavefront illumination beam is projected through a lens that is also used as an imaging lens for a

microscope, a high likelihood of “flashback glint” arises. Even when an optimal antireflective coating is applied to a lens (which likely cannot be achieved for a lens shared by multiple components, as described above), a certain amount of light will reflect from the lens surface as the light enters the lens. This light reflects back into the wavefront sensor, and is seen as a tiny bright flash of light, or “glint.” This glint can obliterate the wavefront information of one or more portions of the eye. Thus, an advantageous feature of the surgical device **10** is that it does not require a lens to be shared by the wavefront sensor **14** and the surgical microscope **12**.

Other advantages result from the detachable nature of the integrated wavefront sensor and surgical microscope, as compared to existing devices that are permanently integrated. For example, the option of adding the compact wavefront sensor **14** to an existing surgical microscope **12**, or of moving the wavefront sensor **14** from one surgical microscope **12** to another, or of removing the wavefront sensor **14** from the surgical microscope for another reason, such as to individually repair one of the devices, provides a great deal of flexibility. A cost benefit may also be achieved, particularly if a component becomes defective, since it is likely cheaper to replace or repair only one of the wavefront sensor **14** and the microscope **12**, than to replace an entire permanently integrated system.

The surgical device **10** may be used to improve and/or enhance a variety of corrective procedures performed on the eye. In general, by providing the ability to measure the refractive characteristics or other optical properties of a patient’s eye while the patient remains lying in a surgical position, several of the limitations of existing systems may be overcome. Several examples of corrective eye procedures that may be enhanced by using the surgical device **10** are described below.

Cataract surgery generally involves replacing the natural lens of an eye after the natural lens has become unclear. Existing methods typically require measuring the physical dimensions of the eye with ultrasound, followed by calculating the refractive power of the artificial lens, or other replacement lens, to be inserted. Because the natural lens is unclear, these measurements are often difficult to make. Additionally, variations in the structures of the eye that cannot typically be measured using existing techniques may degrade the calculation.

The integrated surgical device **10** facilitates measurement of the eye’s refractive power before and/or immediately after the natural lens is removed, without movement of the patient or the patient’s eye, such that the true refractive power of the eye can be more accurately determined. For example, if it is determined that 42 diopters of power are needed for a patient to see clearly at a predetermined distance, and after the natural lens is removed the eye has only 22 diopters of power, then it can easily and accurately be determined that 20 diopters of power must be introduced to the eye via the new lens being inserted.

With existing systems, once the lens is removed, and the doctor wishes to make a wavefront measurement, the patient typically has to be moved from the surgical table to a measurement device to make the refractive measurements. Because the patient is typically sedated, and there may be an incision in the patient’s eye, and there are sterility requirements to maintain, it is not practical to move the patient between surgical steps. By using the integrated surgical device **10**, which is preferably suspended above the patient’s head, conversely, a surgeon may view the patient’s eye through the surgical microscope **12** while the wavefront sensor **14** makes measurements of the eye with the natural lens

removed. Accordingly, the patient, as well as the patient’s eye, is able to remain motionless in the surgical position during the entire corrective process.

A further challenge associated with cataract surgery is that once the replacement lens is inserted into the eye, the replacement lens must be aligned to ensure that it is properly oriented and positioned. If, for example, the replacement lens is not correctly centered, or is not perpendicular to the optical axis of the eye, or if the cylindrical portion (if astigmatic correction to the replacement lens is also being performed) is not oriented to the correct axis, refractive aberrations may be introduced, and the surgical outcome will therefore be degraded. The integrated surgical device **10** allows the surgeon to make refractive measurements of the eye, after the replacement lens has been inserted, which may be used to guide any required repositioning of the replacement lens.

Additionally, during cataract surgery, viscoelastic cushioning fluids are typically injected into the eye to protect endothelium cells and other structures, and should be completely removed after the surgery is completed. The wavefront sensor **14** may be used to identify any remaining viscoelastic pockets (as wave distortions), and can therefore assist the surgeon in removing all of the viscoelastic fluid.

By using the integrated surgical device **10**, astigmatism may also be reduced during the lens replacement procedure by means other than using a replacement lens with a cylinder component. For example, the location and size of any entry wound could be adjusted, the position of a paracentesis incision could be adjusted, as could any additional lamellar, radial, or arcuate cuts made, all while the surgeon receives feedback from the wavefront sensor **14** that may guide corrections made during the procedure.

Additionally, if a replacement lens is damaged during insertion, due to overstress during gripping, nicks and cuts in the lens surface, or damage to the centering haptics, wavefront measurements made after the insertion can identify the damage. Accordingly, the replacement lens may be replaced or repaired before the membrane that previously contained the natural lens shrinks and tightens onto the replacement lens.

A process of introducing relaxing incisions into various locations of the eye, which causes the cornea to flatten out in predictable directions, is often used to eliminate astigmatism of the cornea. Such a procedure is often performed at the end of cataract surgery, for example, to eliminate an astigmatism that was induced by the main cataract incision, or that had previously existed. The amount of flattening generally varies from patient to patient, however, and is therefore very difficult to precisely predict. By using the integrated surgical device **10**, the wavefront sensor **14** can make measurements during the surgical procedure to guide the position, depth, and length of incisions made by the surgeon to achieve desired results.

Corneal transplant surgery, in which a small central portion, typically 8 to 10 mm in diameter, of the cornea is cut from a donor’s eye and grafted into a correspondingly-sized hole cut into a recipient’s cornea, may also be improved by using the integrated surgical device **10**. During the positioning and suturing of the donor’s corneal tissue into the recipient’s cornea, refractive errors are typically difficult to measure. Refractive errors may be introduced if, for example, the donor’s corneal tissue is not properly centered, rotated, or oriented in the recipient’s cornea, or if the sutures are too tight, too loose, or not evenly tightened. If the recipient’s eye is measured after the healing process has completed, refractive errors are difficult, if not impossible, to correct.

By using the integrated surgical device **10**, a surgeon may measure refractive changes in the eye while placing and sutur-

ing the donor graft. Indeed, the recipient may remain lying on the surgical table, and the surgeon may look directly into the visual axis of the recipient's eye, while the refractive measurements are being taken. Accordingly, the recipient does not need to be moved at any point during the transplant procedure. Additionally, the donor cornea may be measured by the wavefront sensor to locate its optical axis to assist with better cutting and/or placement of the cornea.

The integrated surgical device **10** may also be used to enhance LASIK (Laser-Assisted In Situ Keratomileusis) refractive surgery, or other laser-assisted surgical procedures. Several variations of laser vision surgery require that a flap be cut from the surface of the cornea to expose the stroma of the cornea to laser treatment. The laser reshapes the stroma to a desired contour, after which the flap is replaced over the reshaped stroma. If the flap is not precisely repositioned at its original location, if foreign matter is trapped inside the flap, if a wrinkle is introduced during repositioning, and/or if a host of other repositioning errors occur, then the visual outcome of the procedure will be degraded. The integrated surgical device **10** allows a surgeon to measure the refractive or optical properties of the eye while the surgeon directly observes the eye, and while the flap is being repositioned, so that any positioning errors or other problems can quickly be corrected.

The integrated surgical device **10** may also be used during a Conductive Keratoplasty ("CK") procedure. CK is a refractive surgical procedure in which highly localized energy pulses, such as heat pulses or radio frequency pulses, are applied to the collagen or stroma of the cornea to reshape the cornea to correct for refractive errors, particularly hyperopia. Current methods typically require that the eye be measured with a conventional refractive device, which provides information regarding how many energy pulses are required to reshape the cornea as desired and identifies which regions of the cornea should receive pulses. The patient is then moved to a surgical location where the energy pulses, typically 8 or more, are applied to the cornea, after which the patient is moved back to the measurement device so that the eye may be re-measured.

The outcome of such a procedure is generally the result of a best prediction, and the actual outcome is rarely exactly as desired due to variability in the response of each individual cornea. If the cornea is under-corrected, more pulses may be added later, but if the cornea is over-corrected, it is difficult, and sometimes impossible, to reverse the over-correction.

By using the integrated surgical device **10**, the eye's refractive condition may be measured after each pulse is applied (preferably after a certain minimum number of pulses have been applied, for example, after 6 pulses have been applied, since a complete correction will typically not occur until at least a certain minimum number of pulses have been applied), and the surgeon may therefore make guided corrections during the surgical procedure. The surgeon may, for example, alter the position, size, quantity, and/or energy of the pulses applied if measurements taken between successive pulses dictate that such steps should be taken. Additionally, the placement of the pulses is critically important, and the wavefront sensor may be used to help guide the placement of each energy pulse.

A procedure for positioning an inlay in a cornea along the eye's visual axis may also be aided by using the integrated surgical device **10**. In such a procedure, after a flap is created over the cornea, either via a LASIK procedure or another procedure, an opaque disk or similar structure with a small central aperture is placed in the cornea and trapped inside the flap. The inserted disk creates the effect of a smaller aperture, resulting in the depth of view of the eye being increased. It is,

however, extremely difficult to center the disk about the eye's visual axis. By using the integrated surgical device **10**, the wavefront sensor **14** can make measurements to determine the exact location of the eye's visual axis while the surgeon directly views the eye, which aids the surgeon in precisely positioning the disk in the proper central location.

In an alternative embodiment, the corneal inlay's central aperture may be cut into the inlay by the laser after it has been placed in the eye. In such a case, the precise measurements of the wavefront sensor, coupled with the precise control of the laser placement, may result in a more accurate aperture position than if it were manually positioned.

The integrated surgical device **10** may also be used to control corneal distortion during placement of inserts into the cornea. In the case of myopia, for example, the cornea is too steep and must be flattened. In a typical corrective procedure, slices are cut into the cornea, after which tiny, curved strips are slid into the stroma of the cornea to exert a straightening force on the cornea that flattens the cornea. By using the integrated surgical device **10**, the wavefront sensor **14** can make measurements of the eye while the doctor directly views the eye, allowing the doctor to monitor the degree of flattening and to adjust the process (e.g., to add more or different inserts) midstream.

The integrated surgical device **10** may further be used to measure and view the eye during a procedure for adjusting the tension of the ciliary muscle and/or the ciliary process of the eye. In a typical ciliary-tensioning procedure, rings or other devices are inserted into the sclera just beyond the limbus of the eye to exert a radially outwardly pulling force on the ciliary muscle. The goal of this procedure is to expand the relaxed diameter of the ciliary muscle, which in turn provides added tension in the ciliary muscle and removes some of the slack that has developed therein over the years. By using the integrated surgical device **10**, the wavefront sensor **14** can take measurements of the eye while the tensioning procedure is being performed under the surgical microscope **12**, thus guiding the amount of tensioning required to achieve desired results.

Another corrective procedure involves removing tissue from the cornea, via mechanical slicing or another method, to modify the shape of the cornea. In one embodiment of mechanical tissue removal, an incision is made in the side of the cornea to provide a split in the stroma of the cornea. A shallow spoon-shaped device is then guided into the split, and a blade is used to remove tissue below the spoon's edge plane, resulting in less corneal tissue thickness centrally than peripherally, and thus, corneal flattening (i.e., reduction in myopia). By using the integrated surgical device **10**, the wavefront sensor **14** can make measurements during the surgical procedure to guide the process and aid the surgeon in determining how much tissue, at which locations, should be removed.

The natural lens of the eye may also be modified to correct refractive defects in the natural lens. Some defects that may occur over time include small opacities, protein buildup, and size increases in the lens. One method of modifying the natural lens involves removing tissue from the lens to correct vision loss associated with these and other defects. Even a small amount of material removal, however, can result in a large change in refraction. By using the integrated surgical device **10**, the wavefront sensor **14** can make measurements during the surgical procedure to guide the process and aid the surgeon in determining how much lens tissue, at which locations, should be removed.

Optical properties of the natural lens may also be modified by introducing chemicals, or changing blood sugar levels, in

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a patient's system. Using the integrated surgical device **10** during such a procedure allows a surgeon to measure the amount of change resulting from the introduction of one or more chemicals, which can aid the surgeon in reaching a desired outcome.

The integrated surgical device **10** may also be used to aid in controlling or influencing the resulting shape of a lens that is injected into the eye as a liquid and that cures into a solid. Such a lens is commonly referred to as a "form in the bag" lens. Extreme precision is required to attain the desired resultant shape of the lens using such a procedure. During the time period when the material changes from a liquid into a solid, the shape and index of refraction of the lens can be manipulated. Using the integrated surgical device **10** allows a surgeon looking through the microscope **12** to obtain wavefront data about the lens as it is being formed so that proper course corrections can be made during the curing process.

Advancements have been made in the ability to modify or tune the characteristics of an artificial lens after the lens has been inserted into the eye and the eye has healed. By using the integrated surgical device **10**, a surgeon viewing the eye through the microscope **12** can make modifications to the artificial lens while the wavefront sensor **14** makes measurements that can guide the procedure.

Several lenses are available that may be inserted into the eye, while the natural lens remains in place, to modify refractive characteristics of the eye. The correct placement of such a lens is critical to achieving a desired outcome. The integrated surgical device **10** allows a surgeon to view the eye while making wavefront measurements, which aids the surgeon in selecting an appropriate lens and in positioning the lens in the correct central location along the visual axis of the eye. Additionally, the integrated surgical device **10** can verify the overall success or failure of the procedure, which allows the surgeon to make adjustments, while the patient remains on the surgical table, if the outcome is not ideal. This not only improves efficiency, but also allows re-accessing of an incision before it has healed, such that a new incision is not required to make corrections after a non-ideal outcome.

Another corrective procedure involves adding material into the cornea, measuring the resulting refractive condition of the eye, then removing a portion of the inserted material to achieve a desired result. The wavefront sensor **14** of the integrated surgical device **10** may be used to measure the eye before the procedure to help determine a minimum amount of material to add, and may also be used to measure the eye after the material is inserted. The wavefront sensor **14** may then be used to measure the eye at various points of the procedure, which is performed under the surgical microscope **12**, to ensure that the correct amount of material is removed.

During many existing procedures, a patient's eye is measured with a wavefront sensor at a first location, a treatment is calculated and/or planned based on the measurements, and the patient is then moved to a second location where the actual treatment is performed. Typically, the eye is measured while the patient is sitting upright, but the treatment is performed while the patient is lying facing upward in a supine position. When the patient moves from the upright position to the supine position, the patient's eyes rotate, or "cyclotort." To compensate for this cyclotortion, dye marks are typically placed on the eye while the patient is in the upright position so that the amount of cyclotortion can be measured. By using the integrated surgical device **10**, the wavefront measurements may be taken while the patient lies in the supine position, with the cyclotortion present, and while the doctor is viewing the eye. Accordingly, the intermediate step of marking the cornea and compensating for the rotation is not required. The elimi-

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nation of this step improves the efficiency of the process, and the precision of the orientation of the wavefront registration to the eye is enhanced.

While several corrective procedures have been described herein, it is understood that the integrated surgical device **10** may be used to enhance any vision correction procedure by providing a surgeon the ability to view the eye simultaneously with making wavefront measurements of the eye. Thus, the surgeon may make wavefront measurements while the patient remains lying in the surgical position, and may course adjustments to a procedure midstream without having to move the patient between surgical steps.

While several embodiments have been shown and described, various changes and substitutions may of course be made, without departing from the spirit and scope of the invention. The wavefront sensor **14**, for example, could include a greater or lesser number of components arranged in any conceivable configuration. The invention, therefore, should not be limited, except by the following claims and their equivalents.

What is claimed is:

1. A wavefront sensor, comprising:

a first housing having an optical path passing therethrough, and further comprising:

a sensor light source for generating first light;

a detector for capturing wavefront images;

a diffractive optical element; and

a combining optical element for:

receiving the first light from the sensor light source;

receiving second light via the optical path;

transmitting the second light along the optical path towards an eye of a patient;

redirecting the first light to the optical path towards the eye;

receiving reflected first light and reflected second light along the optical path from the eye, the reflected first light comprising the first light

reflected by the eye, the reflected second light comprising the second light reflected by the eye;

redirecting the reflected first light from the optical path via the diffractive optical element to the detector; and

transmitting the reflected second light along the optical path for imaging by a surgical microscope having an imaging light source generating the second light,

wherein the wavefront sensor is enabled for intraoperative refractive measurements of the eye based on the wavefront images captured during surgery on the eye performed using the surgical microscope.

2. The wavefront sensor of claim 1, wherein the optical path and the microscopy optical path enable binocular imaging by the surgical microscope.

3. The wavefront sensor of claim 1, wherein a focal length of the surgical microscope along the microscopy optical path remains the same when the first housing is attached to the second housing.

4. The wavefront sensor of claim 1, wherein the first light includes infrared light and wherein the second light includes visible light.

5. The wavefront sensor of claim 1, further comprising: at least one mirror in the first housing for redirecting the reflected first light.

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- 6.** The wavefront sensor of claim **1**, further comprising:
a partial mirror in the first housing for:
receiving the first light from the sensor light source
redirecting the first light to the combining optical element;
receiving the reflected first light from the combining optical element; and
transmitting the reflected first light via the diffractive optical element to the detector.
- 7.** The wavefront sensor of claim **6**, further comprising:
at least one mirror in the first housing for redirecting the first light from the sensor light source to the partial mirror.
- 8.** The wavefront sensor of claim **1**, wherein the diffractive optical element further comprises:
a first periodic object and a second periodic object separated by an integer multiple of a Talbot distance, wherein the first periodic object and the second periodic object are rotated with respect to one another.

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- 9.** The wavefront sensor of claim **8**, wherein the first periodic object and the second periodic object are diffractive optical gratings.
- 10.** The wavefront sensor of claim **8**, wherein a periodicity of the first periodic object and the second periodic object is based on a wavelength of the first light.
- 11.** The wavefront sensor of claim **1**, wherein the first light includes first visible wavelengths and wherein the combining optical element blocks the first visible wavelengths in the reflected second light transmitted to the surgical microscope.
- 12.** The wavefront sensor of claim **1**, wherein the reflected first light and the reflected second light are scattered by the eye within a field of view of the surgical microscope.
- 13.** The wavefront sensor of claim **1**, wherein the first light and the reflected first light does not pass through a lens of the surgical microscope.

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